PHASE CHANGE MATERIAL CEMENT-LIME MORTARS FOR THERMAL RETROFITTING OF FACADES

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Abstract

The poor thermal performance of many dwelling units built from 1940 to 1980 produces a low energy efficiency under the present thermal standards. In order to fulfil comfort and energy efficiency requirements, these facades need to be retrofitted. In many cases, External Thermal Insulation Composite System (ETICS) are used to increase thermal insulation, although this solution does not consider the thermal inertia. New mortars with improved thermal insulation and inertia are investigated as an innovative solution. Twelve cement-lime mortars were designed, using: white cement, air lime, siliceous aggregate (0-4 mm), lightweight aggregate (LWA) (expanded perlite), short cellulose fibres and 10 and 20% of a Phase Change Material (PCM) - microencapsulated paraffin wax. PCM's nominal melting temperature was 23 ± 1 °C. An experimental program was carried out to assess the effect of PCM on the physical and thermal performance of the mortars. Two different scenarios were considered to evaluate the temperature effect on the PCM-mortar performance. Bulk density, open porosity, capillary absorption, vapour permeability, thermal conductivity and compressive strength were characterized. PCM produced significant changes on the mortar thermal properties and a synergetic effect of PCM and LWA was identified.

Keywords:
Phase Change Material, cement mortar, experimental characterization, thermal inertia, facades' thermal retrofitting.

1 INTRODUCTION

Many dwelling units in Spain built from 1940 to 1980 present a large energy consumption due to their poor thermal performance, when compared to present thermal standards. These façades have also a low thermal inertia which further reduce their thermal properties. Nowadays, façade retrofitting solutions are designed to improve energy efficiency primarily through thermal insulation. The most common solutions are ventilated façade systems and External Thermal Insulation Composite System (ETICS) [Lucas 2010b]. However, those solutions have shown a poor performance in summer conditions [Schiavoni 2016] and do not consider the façade thermal inertia and its influence on energy efficiency. Besides, some issues arise on both systems due to their low adaptability and the thickness increase of the façade.

The design of new mortars with improved thermal properties is an alternative solution for façade retrofitting [Stefanidou 2014, Palomar 2015b]. The former mortars only considered thermal insulation, but thermal inertia is increasing interest in the last years. Phase Change Materials (PCM) have shown to be a very effective solution as mortar components due to their capacity as thermal accumulators without needing active systems [Pavlík 2016]. PCM have a large thermal accumulation capacity during the change from solid to liquid state and vice versa (latent heat), while the material absorbs or releases energy, respectively. The latent heat transfer by the PCM fusion occurs at a certain temperature designated as phase change temperature [Cabeza 2011].

Due to wide variations in their compositions, PCMs can show different characteristics and thermal performance. The most common PCMs are organic because of their low price and commercialization and a higher thermal and chemical stability. Moreover, organic PCMs do not require additives for long-term use and are non-corrosive and recyclable materials. Organic microencapsulated PCMs as paraffin waxes can be mixed with common binders (cement, lime, gypsum) [Lucas 2010a].

This paper presents an experimental program on a PCM cement-lime mortar for thermal retrofitting of façades with an external thermal insulation under specific climatic conditions. The mortars would be placed in the inner side of the insulation (hot side). The effect of a microencapsulated paraffin wax on early age dimensional stability and hardened properties was assessed, measuring free shrinkage, physical and mechanical properties and thermal parameters of twelve cement-lime mixtures.

2 EXPERIMENTAL PROGRAM

2.1 Materials and mortars compositions

The components used in the study were:

- A white cement type BLII/B-L 32.5N (UNE-EN 197-1) supplied by Readymix- Asland S.A.
- An air lime class CL 90-S, designated according to the European standard (UNE-EN 459-1).
- A normal-weight siliceous aggregate (0-4mm).
- A lightweight aggregate (LWA): expanded perlite (L).
- Short cellulose fibres (F) of 1mm length - Fibracel® BC-1000 (Ø20µm) – supplied by Omya Clariana S.L.
- A microencapsulated paraffin wax (Phase Change Material - PCM) with particle size ca. 50-300 µm and a melting point of ca. 23ºC – Micronal® DS 5040 X – supplied by BASF Construction Chemicals Company. Fig. 1 shows an image of PCM.

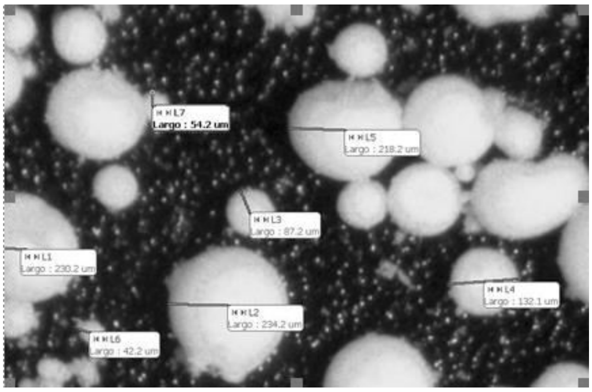

Fig. 101 : Optical micrographs of PCM

Fig. 2 shows a scheme for the mixture composition. A reference cement-lime mixture was designed (C). Then, 10% and 20% by volume of PCM (C_{10} and C_{20}) was added. Afterwards, 1.5% of dry cellulose fibres was added (CF, CF_{10} and CF_{20}). On the other hand 50% of the siliceous aggregate was replaced by perlite (CL, CL_{10} and CL_{20}). Finally a mixture was made adding both fibres and perlite (C, CLF_{10} and CLF_{20}).

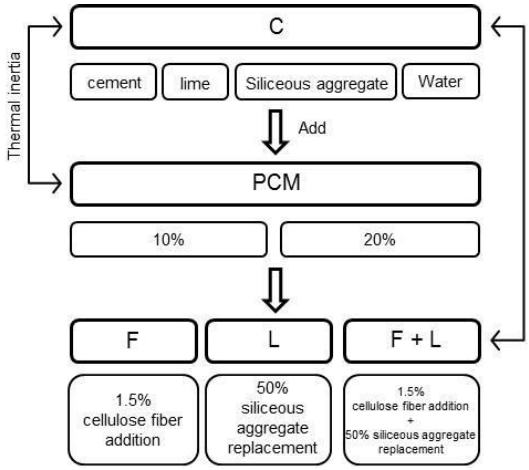

Fig. 102 : Mixture design of PCM cement-lime mortars.

Tab. 1 summarizes the compositions of the twelve mortars of this study. The binder to aggregate ratio was 1: 0.5: 4.5 (cement: lime: aggregate) by volume in all cases. The water to binder ratio (w/b) varied between 0.63 and 0.85 to get a plastic consistency and similar fresh workability for all the mixtures. The dry components, included the fibres and PCM, were mixed first and water was added afterwards. The total mixing time did not exceed 5 min in any case.

2.2 Experimental methods

The experimental program assessed the early age shrinkage (free shrinkage and initial time), physical properties (bulk density, open porosity, capillarity water absorption coefficient and water vapour diffusion resistance factor), mechanical performance (compressive strength and compressive modulus by ultrasonic pulse) and thermal properties of twelve cement-lime mixtures.

Free shrinkage

Early age free shrinkage was monitored on 500 x 100 x 50 mm samples subjected to an airflow of 3 m/s during the first 6 h to force drying shrinkage. The experimental set-up have been previously published [Barluenga 2013]. Only the mixtures without PCM and with 20% of PCM were tested.

Hardened performance

The characterization in the hardened state was done on 40 x 40 x 160 mm specimens. The samples were demoulded at 24h and cured until tested at 28 days (21± 3ºC and 95±5%RH).

The bulk density and open (accessible to water) porosity were calculated using a hydrostatic balance (UNE-EN 1015-10). Capillary water absorption coefficient and, water vapour diffusion resistance factor were measured according to UNE-EN 1015-18 and UNE-EN 1015-19, respectively.

Compressive strength (UNE-EN 1015-11) and ultrasonic pulse velocity propagation (UPV) were tested at 28 days. The compressive modulus (M) was also assessed at 28 days [Palomar 2015a].

Thermal performance

Thermal gradient, T_G (ºC/mm), was measured on 210 x 210 mm and 24 ± 2 mm thick plate samples. A thermally insulated box, with sample openings on its sides, was used. A heat source, connected to a thermal regulator, was located inside the box. Temperature (°C) and humidity (%) sensors were place on the inner and outer surface of the sample and inside and outside the box [Palomar 2015b]. Two temperature scenarios were set in the box: one at 25ºC (5h) and the other one at 40ºC (16h). The laboratory conditions were 20 ± 1^{0}C and 50 ±5% RH during the test (Fig.3).

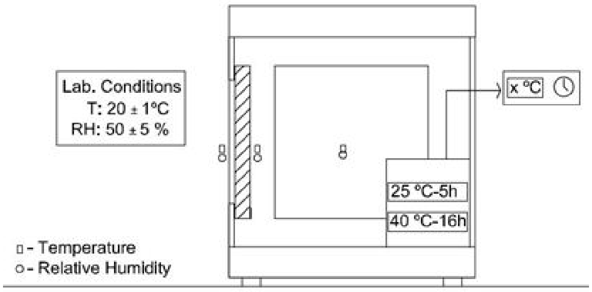

Fig. 103. Scheme of the insulated box.

Tab. 56 : Compositions of the lime-cement mortars (components in Kg).

	Cement	Air lime	Perlite*	Cellulose fibres	Sand 0-4	PCM	Water**	w/b***
C	348	55	-	-	1403	-	220	0.73
C_{10}	348	55	-	-	1403	42.3	140	0.53
C_{20}	348	55	-	-	1403	84.6	200	0.68
CF	348	55	-	0.40	1403	-	220	0.73
CF_{10}	348	55	-	0.62	1403	42.3	180	0.63
CF_{20}	348	55	-	0.66	1403	84.6	240	0.78
CL	348	55	94	-	702	-	240	0.69
CL_{10}	348	55	94	-	702	42.3	240	0.69
CL_{20}	348	55	94	-	702	84.6	250	0.71
CLF	348	55	94	0.49	702	-	240	0.69
CLF_{10}	348	55	94	0.62	702	42.3	305	0.85
CLF_{20}	348	55	94	0.59	702	84.6	380	0.79

** 50% of volume of the siliceous aggregate was replaced by perlite.*

*** Liquid water added.*

**** The amount of water included in the components (sand) was also taken into account. Sand 0–4: Humidity 5.3%.*

3 EXPERIMENTAL RESULTS AND ANALYSIS

Phase change material (PCM) cement-lime mortars for thermal retrofitting of facades were evaluated using the properties summarized in Tab. 2, as maximum free early age shrinkage (S_{FREE}) and initial time (S_{TIME}); bulk density (D), open porosity (P), capillary water absorption coefficient (CC), water vapour diffusion resistance factor (VD); and compressive strength (CS) and modulus (M) at 28 days. The thermal gradient (T_G) is reported in Fig. 4. The influence of the fibres (F) and lightweight aggregates (L) on the properties of the reference cement-lime mortar (C) and the effect of PCM are also discussed.

Tab. 57 : PCM cement-lime mortars' properties

	Shrinkage parameters		Mechanical properties*		Physical properties*			
	S_{FREE} (mm/m)	S_{TIME} (h min)	CS (MPa)	M (GPa)	D (Kg/m^3)	P (%)	CC (Kg/m^{2}min$^{0.5}$)	VD (-)
C	1.30	2h10min	13.7	18.65	1900	19.56	1.02	4.13
C_{10}	-	-	7.7	11.99	1690	16.68	0.48	4.02
C_{20}	1.94	2h00min	7.3	10.66	1600	17.72	0.48	4.29
CF	0.98	2h10min	10.3	19.27	1960	18.93	1.08	3.85
CF_{10}	-	-	6.7	11.83	1720	16.90	0.45	3.57
CF_{20}	0.66	1h50min	6.0	10.23	1660	16.77	0.28	3.47
CL	0.24	2h40min	9.3	11.14	1430	20.95	0.35	3.54
CL_{10}	-	-	5.3	6.49	1180	22.99	0.52	3.63
CL_{20}	0.42	2h00min	6.0	6.35	1270	23.33	0.53	3.62
CLF	0.16	3h10min	13.0	10.92	1430	23.94	0.72	3.80
CLF_{10}	-	-	5.0	4.63	1110	22.10	0.53	3.12
CLF_{20}	0.74	1h40min	5.3	5.61	1160	23.09	0.45	3.26

* *The mechanical and physical characterization were done at 28 days.*

3.1 Early age shrinkage

Tab. 2 records the maximum free early age shrinkage (S_{FREE}) and initial time (S_{TIME}). All the samples shrank, reaching values from 0.15 to 2.00 mm/m. C_{20} showed the highest value (1.94 mm/m) and CLF the lowest one (0.16 mm/m).The start of shrinkage ranged between 1 h 40 min and 3 h 10 min. The mixture CLF shrank the latest, whereas CLF_{20} sample began the first.

As can be observed, the free shrinkage was larger on the reference mixture (C) than on samples with cellulose fibres and perlite (CF, CL and CLF). On the other hand, these components slowed down the initial time, especially CLF. Adding PCM (C_{20}, CF_{20}, CL_{20} and CLF_{20}) increased the value of S_{FREE}, except CF_{20}, and accelerated the initial time, especially CLF_{20}.

3.2 Physical and mechanical characterization in the hardened state

Physical characterization

Bulk density (D), open porosity (P), capillary water absorption coefficient (CC) and water vapour diffusion resistance factor (VD) are summarized in Tab. 2.

Bulk density varied between 1100 and 2000 kg/m^3. The maximum D was measured for CF (1960 Kg/m^3), and the minimum for CLF_{10} (1110 Kg/m^3). It was observed that fibres (CF) increased D, whereas perlite reduced it, even when was combined with fibres (CL and CLF). In addition, the compositions with PCM reduced the bulk density around 300 kg/m^3. However, CL_{20} and CLF_{20} had larger D than CL_{10} and CLF_{10}. Other authors have been reported a decrease of bulk density if PCM was added [Pavlík 2016].

Open porosity varied from 16 to 24 %. CLF had the highest P (23.94%) and C_{10} the lowest (16.68%). As expected, perlite increased the open porosity [Palomar 2015b]. On the other hand, fibres reduced P. The PCM effect on open porosity showed two different trend: compositions with lightweight aggregates (CL_{10} and CL_{20}) increased P, whereas C, CL and CLF mortars had a decrease of open porosity as PCM particles tend to fill the larger pores [Lucas 2013]. Slightly differences were found between 10% and 20% of PCM samples.

The mixtures had capillarity water absorption coefficient ranging from 0.25 to 1.10 kg/m^{2}min$^{0.5}$. CF showed the largest value (1.08 Kg/m^{2}min$^{0.5}$) and CF_{20} the lowest one (0.28 Kg/m^{2}min$^{0.5}$). Perlite mixtures (CL and CLF) reduced the capillarity water absorption coefficient of the reference mixture (C), especially CL. As it can be seen in Tab. 2, there were two groups of PCM mixtures: PCM decreased CC in C, CF and CLF while increased in CL. Therefore, CC followed a trend similar to P [Palomar 2015b]. The amount of PCM did not vary significantly P.

The water vapour diffusion resistance factor oscillated between 4.30 and 3.10. CLF_{10} exhibited the lowest VD (3.12) value, while C_{20} (4.29) showed the highest one. In general terms, fibres, perlite and PCM reduced VD, which means more vapour permeable mortars. Slightly differences were found between 10% and 20% of PCM samples, except for C_{20} and CLF_{20}.

Mechanical characterization

Tab. 2 reports compressive strength (CS) and ultrasonic compressive modulus (M) at 28 days. CS varied between 5 and 14 MPa and M ranged from 4 to 20 GPa. CLF_{10} showed the lowest values of CS and M. On the other hand, the reference mixture (C) exhibited the largest compressive strength and the reference mixture with fibres (CF) the highest ultrasonic modulus values.

As expected, perlite (L) reduced the compressive strength and fibres (F) increased the ultrasonic compressive modulus [Palomar 2015b]. The composition with PCM decreased both parameters, as it has been previously described for compressive strength [Sakulich 2012, Pavlík 2016]. However, there is not a linear relationship between the amount of PCM and the effect on mechanical performance. Adding 10% of PCM meant a higher decrease of compressive strength and ultrasonic compressive modulus than adding 20%.

3.3 Thermal performance

Fig. 4 plots thermal gradient (T_G) at 25 °C ($T_{G,25}$) and at 40 °C ($T_{G,40}$). It can be observed that $T_{G,40}$ was higher (0.2-0.5 °C/mm) than $T_{G,25}$ (0.05-0.15 °C/mm) for all the mortars.

In both temperature scenarios, CLF_{20} sample showed the highest thermal gradient (T_G).

Under 25ºC scenario, CF and CFL without and with 10% of PCM had a very similar T_G. C_{10} and CL_{10} samples had a lower T_G than the reference samples. However, all 20%PCM mixtures showed the highest value.

On the other hand, 40ºC scenario, C and CL, thermal gradient was under 0.3ºC/mm and CF and CFL thermal gradient was 0.3ºC/mm or higher. When PCM was added (C_{10} and C_{20}) TG increased regarding to C.

On the opposite site, the reference mixture combined with perlite and with PCM (CL_{10} and CL_{20}) decreased T_G regarding to CL.

CF mixtures with PCM had different behaviour depending on the amount: CF_{10} showed the same value than CF; and CF_{20} increased T_G.

In CLF mixtures, the more the PCM content the larger the thermal gradient.

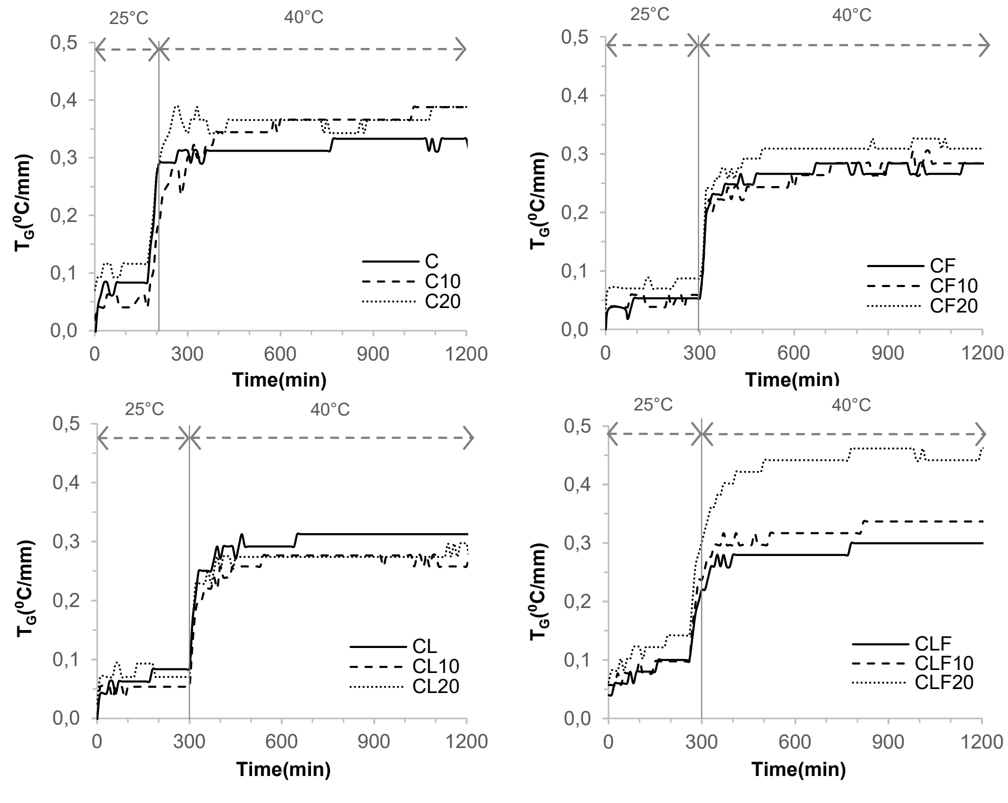

Fig. 104 : Thermal gradient, T_G, (°C/mm of mortar thickness) between inner and outer sample surface at 25 ºC and 40 ºC.

4 SUMMARY

This paper presents the effect of a Phase Change Material (PCM) on cement-lime mortars properties. Short cellulose fibres (F) and a lightweight aggregate (L) (expanded perlite) were also added. The experimental program assessed the early age shrinkage, hardened physical and mechanical properties and thermal behaviour.

The main findings of the study can be summarized as:

- The use of FC, L and PCM modified the properties of a reference cement-lime mortar. The water to binder ratio (w/b) varied slightly to get a similar consistency and workability.
- Compositions with LWA (CL) reduced and slowed down the early age shrinkage, especially with fibres (CLF). On the other hand, PCM had the opposite effect.
- Adding FC, L and PCM affected the pore structure parameters - open porosity (P), capillary water absorption coefficient (CC) and water vapour diffusion resistance factor (VP) – and mechanical properties. PCM modified the pore structure reducing P, CC and VP on C, CF and CLF samples, but increasing them on CL mixtures. Regarding mechanical performance, PCM reduced both parameters, compressive strength and ultrasonic compressive modulus.
- In general, the amount of PCM did not affect significantly the pore structure and mechanical performance.
- Thermal performance of PCM cement-lime mortars was affected by temperature scenario and components as cellulose fibres and expanded perlite. Thermal gradient at 25 °C ($T_{G,25}$) was lower than 40 °C ($T_{G,40}$).
- The 10% PCM samples had a different thermal gradient ($T_{G,25}$ and $T_{G,40}$) depending on the reference mixture. On the other hand, a larger amount of PCM (20%) increased the thermal gradient (T_G), especially on CLF_{20} at 40ºC scenario. However, PCM decreased $T_{G,40}$, on CL mixture.

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